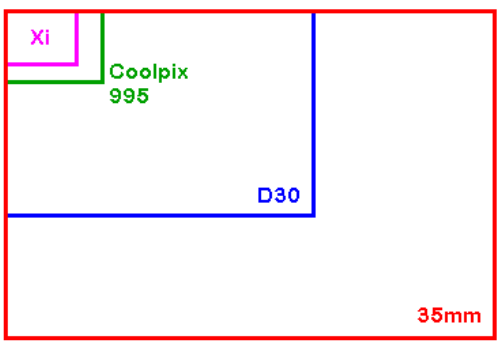
Size Matters

by Bob Atkins

There's a lot of attention paid in the digital camera world to pixel count. Cameras are often categorized by the number of pixels they have in their image sensor. However not all pixels are equal and, as in many contexts, size matters!

In this article I'm going to take a look at several digital cameras with different physical sensor sizes but all with a nominal 3 megapixel (3MP) pixel count. A standard 35mm frame is 36mm x 24mm, so lets call that "full frame". As you can see from row #1 in the table, all the cameras listed here have sensors smaller than a "full frame sensor". Just looking at the "short" side of the sensor compared to the "short" side of the 35mm frame we can see that the Canon D30 sensor is 0.63x full frame, the Nikon Coolpix 995 0.22x full frame and the Minolta Xi sensor is 0.167x full frame. You can see the difference in relative sensor size from the figure below. It's pretty dramatic!



"So what" you might think, "if you have enough pixels, what does the sensor size matter?". Cameras with smaller sensors use shorter focal length lenses to get the same angular coverage as cameras with larger sensors do with longer focal length lenses. So if you have a 28-105mm zoom on a Canon D30, a 10-37mm zoom on a Nikon 995 or a 7.4-28mm zoom on a Minolta Xi, you get approximately the same shot. What's the big deal about the physical size of the sensor? Why does it matter?

One reason why sensor size matters is shown in the table below which I'll go though line by line since it's a little complex! Please note that the numbers are intended only for illustrative purposes and in some cases may be approximations or upper limits. These numbers are not intended to be accurate predictions of the exact resolution you would see from these cameras in practice. However the trends which these numbers illustrate certainly *can* be seen!

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		Canon D30	Nikon Coolpix 995	Minolta Xi
0	"Sensor size"	-	1/1.8"	1/2.7"
1	Physical size (mm)	22.7 x 15.1	7.2 x 5.3	5.3 x 4.0
2	Size (pixels) [all nominal "3MP"]	2160 x 1440	2048 x 1536	2048 x 1536
3	Print size for 8x10 crop	8 x 12	8 x 10.7	8 x 10.6
4	Magnification for 8x10 crop	13.46x	38.3x	50.8x
5	Sensor pixels/mm	95.4	290	384
6	Sensor resolution limit	47.7 lp/mm	145 lp/mm	192 lp/mm
7	Max resolution 8x10 print	3.54 lp/mm	3.78 lp/mm	3.78 lp/mm
8	Sensor Resolution needed for 3 lp/mm in an 8x10 print	40.4 lp/mm	115 lp/mm	152.4 lp/mm
9	Corresponding MTF @ f8	0.75	0.31	0.14
10	Corresponding MFT @ f4	0.87	0.64	0.53
11	Corresponding MTF @ f2	0.94	0.81	0.76
12	Corresponding MTF @ f16	0.50	0.00	0.00

- Line 0 is the industry name for the sensor size. Quite misleading and confusing!
- Line 1 shows actual the physical sensor size (in mm)
- Line 2 shows the size of the sensor in pixels
- Line 3 shows the minimum print size needed for an 8x10 cropped image
- Line 4 shows the magnification of the sensor needed to make an 8x10 image
- Line 5 shows the number of pixels per mm in the sensor

- Line 6 shows the theoretical resolution limit of the sensor ("Nyquist limit")
- Line 7 shows the maximum resolution you can get in an 8x10 cropped image

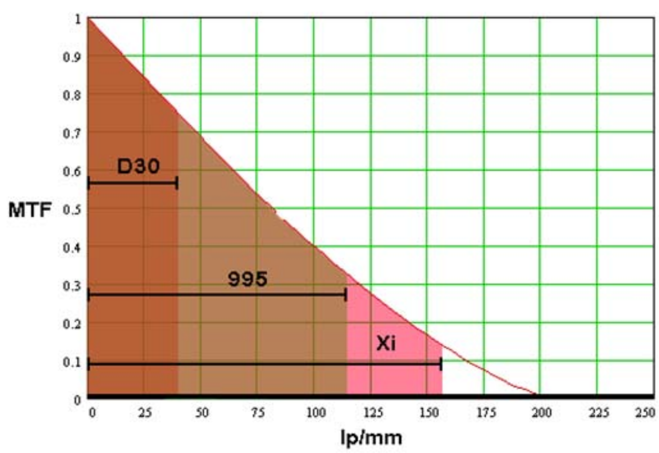
OK, so those are the basic facts. Now lets take an example of an 8x10 print and let's say we want a fairly sharp print, so we are going to need a resolution of at least 3 lp/mm in the print. First, by looking at line 7 we can see that that's possible with all three cameras. Now for 3 lp/mm in the print, what resolution do we need from the sensor? Well, that's given in row #8 of the table. Since the smaller the sensor the more the image needs to be enlarged, to get the same resolution in the same sized print we need more resolution from smaller sensors. The table shows that for the D30 we need to record the image at up to 40.4 lp/mm on the sensor. For the Coolpix 995 we need to record 115 lp/mm on the sensor and for the Xi we need to record a whopping 152.4 lp/mm on the sensor.

Now we get to MTF (Modulation Transfer Function). This is a measure of lens performance and shows how well a lens reproduces object detail in the image it produces. I'll deal with MTF and exactly what it is in a future article, but for now it's enough to know that MTF can range from 1 to 0, and that high numbers mean high contrast, resolution and image fidelity, while lower numbers mean lower contrast, resolution and image fidelity. You want high numbers!

Line 9 of the table shows the MTF of a perfect lens operating at f8 when recording detail on the sensor at the resolution given in line 8 of the table. So for the D30, we need 40.4 lp/mm on the sensor, and at 40.4 lp/mm a lens operating at f8 will have an MTF of 0.75. For the Coolpix 995 we need 115 lp/mm on the sensor, and at 115 lp/mm a lens operating at f8 will have an MTF of 0.31. Finally for the Xi we need 152.4 lp/mm on the sensor to get 3 lp/mm in an 8x10 print, and at 152.4 lp/mm an f8 lens has an MTF of 0.14.

Lines 10 and 11 show the corresponding numbers for a perfect lens at f4 and f2. The larger sensor is still better, but the difference is less pronounced. Note however that the data here is the best possible case. In practice lenses are not perfect and the faster a lens is, the less perfect it is. Real MTF drops off much faster than that predicted for a perfect lens, so the differences in MTF between sensor sizes will actually be greater than the analysis here shows, especially at wide apertures, giving an even greater advantage to the larger sensors.

So its clear that the larger the sensor, the higher up on the MTF curve of the lens it's operating at when delivering a particular resolution and the final output is a print of a given size. This is shown graphically in the figure below.



This graph shows where on the lens' MTF curve each of the 3 cameras operate when at f8 and used to make an 8x10 print with detail up to 3 lp/mm in the print. As you can see the D30 uses the high part of the MTF curve and so yields an image of good contrast and resolution all the way up the the required 3 lp/mm. The Coolpix 995 with a significantly smaller sensor has to use part of the MTF curve which is lower than that used by the D30, and the Xi with the smallest sensor of all has to use almost the whole MTF curve, even the low part. The range of the curve used depends *only on the size of the sensor*, so we could replace the "D30" label with 22.7mm x 15.1mm, the "995" label with 7.2mm x 5.3mm and the "Xi" label with 5.3mm x 4mm.

Since all three of these cameras are nominal "3MP" cameras, we can predict that results from the D30 will be better than those from the Coolpix 995, which will in turn be better than those from the Xi, assuming we use a lens of the same optical quality on each camera.

One final interesting point is shown by row 12 of the table which shows the MTF at f16. The D30 sensor is OK but using the 995 sensor or the Xi sensor the MTF *is* zero! What this means is that there would be a significant drop in image quality operating at f16 with either the Coolpix 995 or the Xi. In fact we *could not* obtain the desired 3 lp/mm in an 8x10 print if we were able to stop the lens down to f16 on those camera. That's why the smallest aperture available on these and most other small sensor cameras is f8.

So now you know why "bigger is better" when it comes to image quality and digital sensors. Of course bigger is also more expensive, and bigger means bigger (hence heavier and more expensive) lenses, so you can see why many digital cameras stick with small sensors. It's cost, not quality that keeps sensors small.

Readers' Comments

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Gurpreet Singh Bhasin , August 17, 2003; 02:22 A.M.

Very informative. Thank you Bob, for another of your great insights into digital imaging.

Per Ofverbeck , August 17, 2003; 10:16 A.M.

Well, this is a quantitative confirmation of the old rule that one mustn´t stop down a lot if using small format! The classic Minox sub-mini had a fixed aperture of f/3.5 (plus a curved film plane), and my Digital Ixus, at least, always shoots wide open (there is an ND filter that is used in strong light; the EXIF data reports its use as a smaller f stop). I don´t know if this is the case for all small-sensor digicams.

Also, this shows that there isn´t much sense in providing more modes than Program in a small digicam! The program keeps the aperture open as long as possible, shortening exposure time first, which is the best you can do in virtually all situations. Exposure compensation really gives all the control you need, preferrably combined with spot metering.

Charles Miller , August 17, 2003; 12:10 P.M.

Bob,

Thank you for publishing this very valuable and timely article. I think anyone considering a digital camera would be very well advised to read it. Your professional contribution represents photo.net at its very best.

Regards,

Arthur Yeo , August 17, 2003; 04:10 P.M.

Clear & concise article.
Have to agree with the gist of the article but for the sake of convenience, a "tiny" p+s digicam is invaluable for informal snapshot type of images.
On the other hand, if size is really what one is looking for in terms of printing a hardcopy that is 4ft wide or larger, then scanning in a 4"x5" negative/transparency using a Tango scanner seems like a better route to go.

Bob Atkins , August 17, 2003; 04:32 P.M.

True - but the goal of the article isn't to tell you how to make big prints!

The goal is to point out that pixel count isn't everything, and there are good, sound, scientific reasons why a 4MP full frame 35mm image may in fact be better than a 10MP image from a sensor the size of your fingernail.

It's not to say more pixels aren't better, but that there are pixles and then there are pixels. Not all pixels are equal and there may be good reasons to chose a camera with less pixels and a larger sensor than a camera with more pixles and a smaller sensor - all else being equal.

The fact that you CAN get pretty good images out of a tiny sensor is great, since it means you can make really tiny cameras, just realize those tiny cameras have their limitations, especially in terms of DOF, aperture restrictions and ultimate image quality - and they still would even if they were 25 megapixels!

Matt Kime , August 17, 2003; 08:06 P.M.

One thing about this article that confuses me is how aperture relates visually across the format sizes. Yes, f16 is unusable on the smaller sensors. I might shoot at f45 on my 4x5 camera, but there's just no need for that on my 35mm.

If i'm shooting with a 150mm lens at f16 on a 4x5, what is the visually corresponding f-stop on 35mm?

Jorge Oliveira , August 17, 2003; 09:02 P.M.

There is an interesting aspect in this article:

The lowering in prices of silicon chips has always been made through 'shrink' - that is, make the silicon smaller.

If we have an optical barrier to it, it means high quality digital will be expensive for a long time to come...

Pete Su , August 17, 2003; 10:11 P.M.

One more thing to point out about sensor size is that it has a great effect on the noise present in the final digital file.

Comparing my S30 point and shoot to a Nikon D100, you find that the D100 is better at ISO 400 (or even 800) than the S30 is at ISO 100 or 200.

Bert Armijo , August 18, 2003; 12:54 P.M.

>> The lowering in prices of silicon chips has always been made through 'shrink' <<

Although many components do get less expensive because they can fit on smaller pieces of silicon as feature geometry shrinks, that isn't the only source of cost reduction. Although I have no "inside" information, given the size of the sensor I believe yield is probably the constraining factor in sensor cost. As feature geometry shrinks and manufacturing processes mature, yield improves substantially and costs come down. As an example, look at the cost curve for LCD displays. I expect we'll see more full-frame sensor cameras and a general erosion of the price premium for them over the next five years.

At that point, digital photographers will be in the same boat as film photographers - trying to afford the next great piece of glass in their collection.

Joey Sandoval , August 18, 2003; 01:19 P.M.

Impressed, I am. Like Yoda, I speak.

. Kaa , August 18, 2003; 03:15 P.M.

There is extensive discussion of the implication of sensor (and pixel) size on image quality on Norman Koren's site -- see e.g.

http://www.normankoren.com/Tutorials/MTF7.html

Kaa

Dennis Bolling , August 19, 2003; 05:47 A.M.

In regards to the cost factor for the electronic components of digital cameras. There are two factors that are involved.

The one that you've already touched on, the cost of production, drops very slowly, usually only with improvements in production technology and efficiency.

The other is the reseach and developments costs that are built up before the component ever goes into production. It is usually these costs that drive up the initial release cost of electronics, and after they are paid off in a year or two of sales you see the price start to drop to a level driven by the production costs.

Unfortunately in our current market new and improved products come out so fast that a better version comes out before the price on the older one has a chance to drop, and often enough they will discontinue the older model one the R&D costs are paid off in order to force people to upgrade and to keep their profits up.

Toby Cline , August 19, 2003; 10:43 A.M.

Maybe I'll just buy a 35 mm compact camera for 150 bucks, instead of that 550 dollar compact digicamera . . . and make an 8x10 with crushing resolution that'll whip 'em all!

Qiang Lin , August 19, 2003; 01:34 P.M.

I totally agree that sensor size is important, pixel count is mostly for marketing purpose. But one point I have to make here is that shooting a film P&S doesn't guarantee good image quality either. I noticed that the prints made by cheap chain stores are not impressive, probably because everything was done automatically, and the machines are tuned for highest speed instead of highest quality. When I got the prints from my Olympus C4000, I was stunned by the good quality. Then I guess for the same reason, if you give them a reasonable quality digital image, there is no loss in their scanning process. Therefore, you can get better prints at a lower price.

Erb Duchenne , August 20, 2003; 02:31 P.M.

If 8x10 is pretty much as big as you'll want to print, I'd have to say 3 Megapixel can be excellent. You might not be able to tell the difference between digital and film.

But this article truly answers what I've been asking many people and on many forums, photo.net included.

Obviously pixels do matter. But so does the size of the sensor. This means a 6.3 MP sensor at 35mm would be better than the 6.3MP APS-C size used by the EOS 10D. And a 10 MP sensor at the 10D size is better than the 10D. So things are getting clearer. Thanks Bob.

Giampi . , August 20, 2003; 08:10 P.M.

GREAT ARTICLE! I think one VERY practical finding from this is that if one is in the market for an easy to carry P&S digital, spending more $$$ for increased "megapixels" may not necessarily bring better pix.

Ron Karpel , August 23, 2003; 11:47 P.M.

Most of what we are talking about here applies to film as well as digital.

Another advantage for the larger frame is the amount of light actually reaching the sensor/film. A given aperture means larger diaphragm opening (physically) for a larger frame. Allowing more light (count photons) to reach the sensor/film. A larger sensor with the same number of pixels as a small one, will have more light (photons) hitting each pixel. This in turns means better dynamic range and less noise. A camera

with a small sensor will need to amplify the signal from each pixel more increasing the noise level.

Ron

Bob Atkins , August 28, 2003; 05:34 P.M.

I didn't go into noise comparisions, but digital image noise has two fundamental components. Photon shot noise and thermal shot noise. Photon shot noise dominates at high signal levels (short exposure) and comes from the basic statistics of photon detection. Thermal shot noise comes from the dark current of a sensor and is strongly correlated with temperature (lower temperature give lower noise). This is the noise that dominates long exposures.

Noise from both sources gets worse with smaller pixels.

There are also other noise sources of course, which depend on the design of the sensor array and quality of components, but in principle these other sources can be reduced to levels below those of photon and thermal shot noise. A good array with large pixels will always show less noise than an equally good array with small pixles.

Greg Erker , August 30, 2003; 03:11 A.M.

Thanks for the article Bob. How about a page 2 that compares the different sensor sizes when shooting an 8x10 to produce equivalent depth of field? For landscape shots that would seem to be a more fair comparison (eg. I need from here to infinity in focus).

Thanks - Greg

Marc Desimpelaere , September 03, 2003; 07:58 A.M.

Very educative! But there's another reason why you don't want a small sensor: in fact pixels are so small with the small 1/1,8" CCD (about 3 µm) that noise is far greater (and more annoying) with this kind of sensors than with the CMOS the EOS 10D (for example) uses. Everyone wants more pixels, not really knowing why since they never have the intention to male 10x8 prints of their photo's. And wanting more pixels, they get more noise, thus less image quality.

I had the possibility of using 5 MPixel Point-and-Shooters. All but one failed in this aspect. A good and 2 times cheaper 4 MPixel (like the IXUS 400) delivered better images at 100 ISO setting (can you imagen how bad the 5 MP score at 400 ISO setting?). The one who actually wás better than the digital Ixus was... the Powershot G5 which had comparable noise at 400 ISO, but was by far better at 100 ISO setting. Nice!

Dan Marder , October 27, 2003; 05:42 P.M.

Very informative article, and something I've been pondering wrt my "what next" decision. Isn't the logical conclusion that Foveon-type sensors are the only way to go (big pixels)?

However, Foveon aside, there appear to be real-world considerations which somewhat mitigate the advantage of larger sensors.

My compact (I'd like a DSLR but don't have one yet) has an f/1.8 zoom which is crisp wide open, and optimum by f/2.3. That's about 2 stops faster than DSLR lenses.

I compared the resoution (not overall image quality) of my 5mp compact with a 6mp dslr, using a manually-focused high quality prime. The compact peaked at f/2.3, the DSLR at f/5.6 : identical resolution.

Of course the compact was about 2 stops noisier at any iso, but again there's that 2-stops-faster, lens...

So far the only thing completely obvious to me is that one should use lenses designed specifically for the sensor size.

Dan

Hans-Peter Lammerich , January 15, 2004; 04:50 A.M.

The tiny sensor sizes of □prosumer□ digital cameras allows for relatively fast lenses with gigantic zoom range which is an intriguing feature for many amateurs not willing to carry multiple lenses, even less prime lenses. Remember the late 1970s super-8 cameras with 10x zoom and f1.2. In digital land we now have f2.0-2.8/7-50mm lenses, being equivalent to f2.0-2.8/28-200 for 24x26mm, with probably 30cm front lens diameter and 30kg weight.

I however understand from reviews that, even with a Zeiss badge, optical performance is not that great. In fact in 35mm land, Canon□s or Nikon□s f2.8/80-200s are still not up to the level of prime lenses and the f4.5-5.6/28-200 Tamron/Sigma/Tokina are even less.

Sony□s/Zeiss f2.0-2.8/7-50mm lens is not greatly smaller than a f4.5-5.6/28-200 from Tamron/Sigma/Tokina, but I understand a Canon 1Ds and even a 300D set to ASA 400 exhibit less noise than a Sony F828 set to ASA 100. In this regard the lens specs are misleading. A side-by-side comparison of small sensor, fast lens low ISO setting against large sensor, slow lens, high ISO setting would be interesting.

Apart from the sensor size issue, e.g. Olympus claims that their lenses for the new E-1 are somewhat optimised for the digital sensor. To some extend I can follow the arguments, but this approach seems not to yield in better image quality (www.dpreview.com), compared to DSLRs connected to conventional lenses designed for 35mm film.

Rob Kerkmann , August 28, 2004; 12:20 P.M.

I'm still unclear. I figure that I want print resolution at about 300 pixels per inch in PS, and therefore, unless I resample up, I am restricted in the size of photo by the number of my original pixels. If the bigger size CCD (but with the same pixel size) leaves me with the same number of pixels, can you explain how or why I get better pictures with a bigger CCD, or why I get a file that allows me to print larger pics? Is it because, with the larger CCD, the accuracy of the capture (each pixel) is better, and therefore the original unsampled pic is better and an up-sampled pic would therefore be better too. I'm guess I'm looking at this too simplistically.

Achim Schumacher , October 08, 2004; 06:03 A.M.

>>In digital land we now have f2.0-2.8/7-50mm lenses, being equivalent to f2.0-2.8/28-200 for 24x26mm, with probably 30cm front lens diameter and 30kg weight.<<

I think there is a general misconception of the aperture values when comparing different sensor sizes, and Matt Kime above already gave the correct hint.

An f2.0-2.8/7-50mm lens on a small sensor is NOT equivalent to a f2.0-2.8/28-200mm lens on 35mm format! We are all used to apply a "cropping factor" to calculate the equivalent focal length, but we should do this also to the aperture value, in order to get an "equivalent f-stop". Then, the lens would be an equivalent f8.0-11.2/28-200mm lens. It's just that no manufacturer would like to name it this way.

But think about it:

1) For an equivalent depth of field, it is the actual diameter of the lens aperture that counts. Since the f-number N is defined as the focal length f divided by the aperture diameter D, we get $D=f/N$. If we multiply f by the crop factor, then we have to multiply N by the same factor in order for D to be constant. Take an online DoF-calculator to test yourself. If you have 2 cameras with different sensor sizes and lenses so that the Field of View is the same, then to obtain the same DoF, you need to stop down the larger camera by a factor equal to the cropping factor.

2) For the same noise level, we need the same amount of photons entering the lens. In other words, it is again the actual diameter of the lens aperture that counts. Smaller sensors show higher noise, because at the same ISO value (which is defined by the real f-value, not the equivalent f-value) and according exposure time, there is less light collected. (This assumes the underlying technique to be identical, just

scaled in size, e.g. the number of pixels being identical). We see, we have to multiply the ISO value by the square of the crop factor to get an equivalent ISO! (We need the square, because the incoming light depends quadratically on the aperture diameter). We then could even use the equivalent f-number together with the equivalent ISO value in order to calculate the correct exposure, just as a valid alternative to using the real values.

CONCLUSION: if we want to compare cameras with different sensor sizes (crop factor C) but with lenses to obtain an equivalent Field of View, it is not sufficient to use the equivalent focal length (f2=f1/C), but we also have to calculate equivalent aperture values N and ISO values: N2=N1*C and ISO2=ISO1*C*C.

Now, an f8.0-11.2/28-200mm lens won't autofocus on an SLR! This is no contradiction, because the AF-system on a SLR is independent from the sensor size, and relies on the light flux coming in, which is dependent on the real, not the equivalent f-number.

To Bob's comparison: You would not want to stop down a 1/1.8" sensor camera (C=5) to f/16, because this is equivalent to f/80 on a 35mm size camera, which would also yield to an almost zero MTF, I guess.

I wonder why up to now not a single digital camera reviewer found out about this equivalent f-stops and ISOs and bases his reviews on these values. It would help compare cameras and understand the differences.

Wayne Herbert , April 10, 2005; 11:26 P.M.

Thank you for an informative article. I now understand why my Panasonic FZ-20 has a maximum of an f8 setting.

I must say that line 4 of the chart doesn't seem very useful. Since a pixel is the smallest level of granularity, its color will be uniform, and its value will be some 24 (or 32) bit number that can be painted into as large an area as required with no loss of fidelity.

Anil Singhal , June 01, 2007; 01:00 P.M.

Thank you so much. Lovely information. It has always bothered why f8 is the maximum I could ever find on a digi cam. and lot more I know now, why my D SLR is a better machine

Dainis Dērics , March 05, 2008; 06:42 A.M.

Very useful. Thanx!

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